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              ATHENS DEPT OF PHYSICS M G MENENDEZ JUN 87
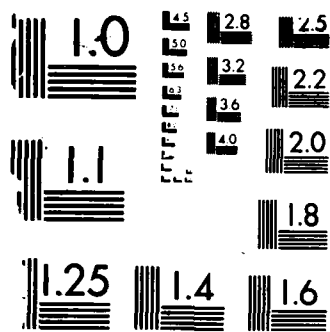UNCLASSIFIED AFOSR-TR-87-0894 AFOSR-83-0264   F/G 7/4   NL

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This research has had as its main thrust the detailed investigation of the electron loss processes of H- in collisions with neutral atoms (mainly He) and some measurements associated with projectile excitation in ion-atom collisions. Measurements have been made on the energy spectrum of detached electrons at a laboratory scattering angle of zero in coincidence with Lyman-alpha photons from the excitation and subsequent decay of H(2p) produced during the process, H- + He becomming H(2p) + e- + He*, at 0.5 MeV incident ion energy. It was found that this electron energy distribution mimics the so-called very sharp peak feature of the doubly differential cross section previously measured under e- and H coincidence conditions. This result shows that excitation of H is responsible for the very sharp peak and that the detached electron energy distribution associated with H(2p) is significantly different from the distribution associated with the production of H(1s).

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This body of research has had, as its main thrust, the detailed investigation of the electron loss processes of H^- in collisions with neutral atoms (mainly He) and some measurements associated with projectile excitation in ion-atom collisions.

At the time this grant was awarded, good electron energy spectra (DDCS) for electron loss from H^- in collisions with He were available due to previous work in this laboratory. These DDCS showed structure in the forward direction, $\theta < 3^{\circ}$. This structure consisted of two peaks. Very near 0°, the highest energy peak was measured to occur at an electron energy, $E_e = 1/2\, M_e v_i^2$, where v_i is the ion velocity. (This is usually referred to as $v_e = v_i$.) The lower energy peak, about 30eV below E_e, was not nearly as sharp. Theory[1] was able to produce a two-peaked structure near 0° due to interference between the $\rho = 0$ and $\rho = 1$ outgoing partial waves of the electron. However these calculations treated only the single electron loss (SEL) process producing H+e while ignoring double electron loss (DEL) which produces H^++e+e. Although the comparison between theory and experiment was qualitatively good, there remained some problems. Considering the SEL process, the calculations predicted the energy of the high energy peak to be slightly higher than the E_e given above. Further, the ratio of the two

peak heights near zero degrees was calculated to be less than was measured in experiments when both SEL and DEL electrons were detected. A further preliminary calculation for SEL when H was left in an excited state produced a DDCS with a single peak which was highly angular dependent.[2]

Our research project focused on the following questions which arose when improved measurements were compared with theory:

1. Are there any features of the DDCS which have not previously been seen which could be attributed to either SEL or DEL?

2. What is the DDCS of DEL electrons alone?

3. What is the DDCS of SEL electrons alone?

4. Can theory and experiment be brought into better agreement?

5. What is the nature of the DDCS of SEL electrons associated with excitation of the resulting H atom?

These issues were, for the most part, resolved and other new results were discovered.

Question 1 was addressed in Reference 3 where high energy and angular resolution spectra were taken near $0°$ for different velocity ions (.15 to .7 MeV/u) using two different targets (He and Ar). One new feature was found. Because of a change in slope on the high energy side of the sharp peak at E_e, it seemed that this peak was a composite one with a very sharp peak centered at $v_e = v_i$ sitting on top of a broader peak. (See Fig. 1.) This very sharp peak was extracted from the data. (See Fig. 2.) This sharp peak, when viewed from the frame of the

moving projectile, was found to have the same probability for ejection at 0° as at 180° in this frame. This relative probability was also the same for all velocity ions and both targets. (See Fig. 3.) It was presumed that these electrons were due to (a) DEL or (b) other SEL processes than those theorists usually discuss. This was explored in greater detail and it was later shown that, in fact, this very sharp peak does belong to SEL, and further, that in the projectile frame, the angular distribution of these electrons (with a given energy) is isotropic (see Fig. 4).

Question 2 was investigated in Reference 5 where the DDCS of 0° electrons from H^-/He collisions which were coincident with H^+ were measured. As seen in Fig. 5, the DDCS at 0° has no structure and is peaked at $v_c = v_i$. Thus, at this time, the question of the source of the very sharp peak was still uncertain.

Question 3 was answered in Reference 4 where electrons were measured in coincidence with H atoms. The DDCS at 0° shown in Fig. 6 has exactly the same structure as seen in the DDCS when no correlation requirement is used. Thus, we concluded that the very sharp peak seen with no correlation requirement (see Fig. 1) is due to an SEL process. The conjecture was made that this very sharp group of electrons might be the signature of the production of $H(n\ell)$ rather than $H(1s)$ in the final state.

Question 4 was investigated by the work reported in Reference 6. A by-product of the analysis of the DDCS used to extract the very sharp peak was that the underlying peak has a

peak energy greater than E_e. This is shown in Table I where $\overline{E}$ = energy of peak, $1/2 M_e v_i^2 = E_e$, and $\delta\theta$ is the angular range which was used to determine $\overline{E}$.

Question 5 has been answered in Reference 7 where electrons at $0°$ were measured in coincidence with Lyman α photons, thus, giving the DDCS of electrons from collisions in which H was left in the 2P excited state or from a cascade to this state. The DDCS is shown in this paper. Please note that the shape ot this $(DDCS)_{\hbar\omega}$ agrees qualitatively with the DDCS of the very sharp peak, a result not unexpected. (A preprint of this work is included in this report.)

Another piece of research completed during the time of this grant is reported in Reference 8. The aim of this investigation did not have anything directly to do with the electron loss of ions but it did allow us to sharpen our experimental skills necessary to accomplish coincidence measurements with very high count rates which were a part of this research.

This grant has provided the opportunity to make detailed investigations of electron loss of H^-. Much progress has been made in establishing the significance of both target and projectile excitations in ion-atom collisions. This work has stimulated considerable interest among theorists who are busy addressing some remaining questions regarding the SEL process.

Altogether, there have been six publications on this work and two students, J. L. Hopkins and C. B. Mauldin, have received M.S. degrees.

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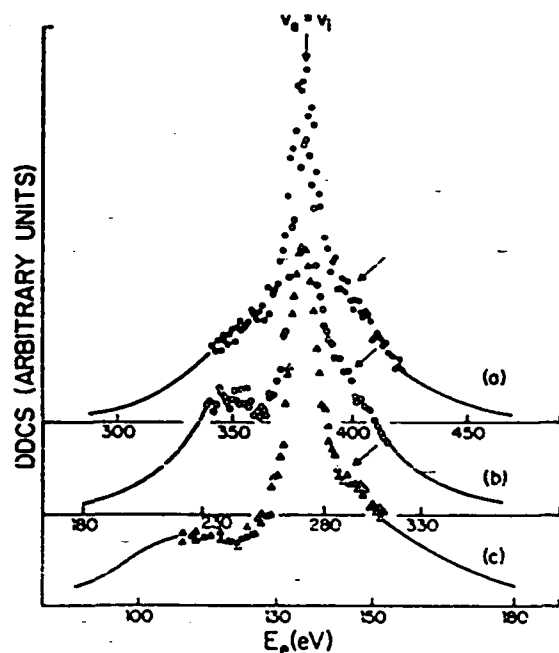
FIG. 1. DDCS at $\theta_L = 0°$ for three different velocity ions: (a) 0.7 MeV H⁻/Ar, (b) 0.5 MeV H⁻/He, and (c) 0.5 MeV D⁻/He. The changes in the slope referred to in the text are indicated by the arrows. Smooth lines have been drawn through data points in the energy regions of little interest.
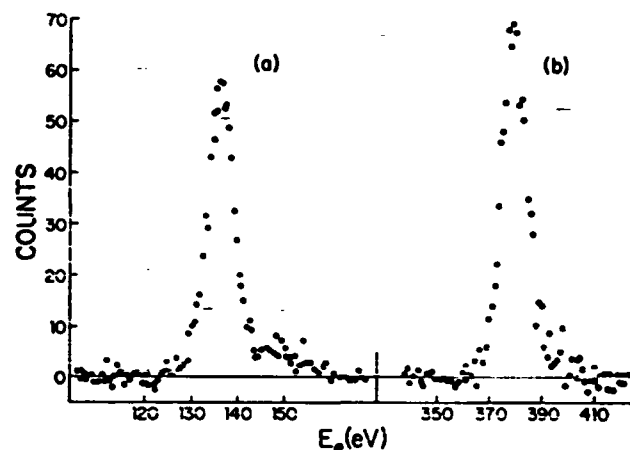
FIG. 3. Shown are the sharp peaks resulting from the normalization and subtraction procedures referred to in the text. (a) DDCS (0°)-DDCS (2.3°) for 0.5 MeV D⁻/He. (b) DDCS (0°)-DDCS (1°) for 0.7 MeV H⁻/Ar.
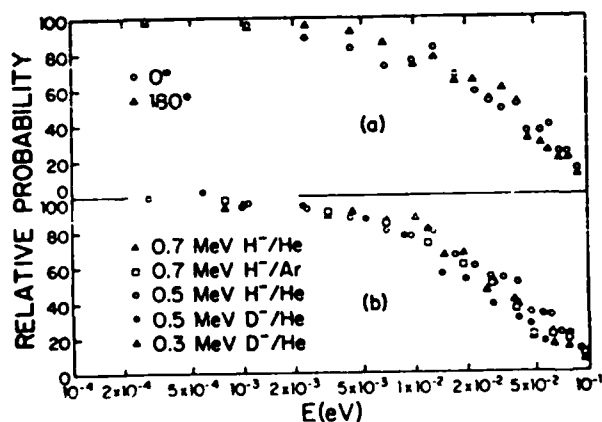
Fig. 1 - From Ref. 3.

Fig. 2 - From Ref. 3.

FIG. 4. The laboratory probability (relative) plotted as a function of the energy of the electron in the rest frame of the projectile as calculated from Eq. (1). (a) 0.5 MeV H⁻/He showing forward and backward emission in the projectile frame. (b) The results of all the experiments normalized to the 0.5-MeV H⁻/He results as explained in the text. Forward and backward data have been averaged.
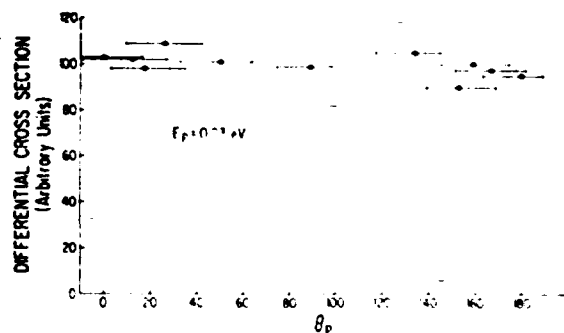
FIG. 5. An angular distribution of 0.03-eV electrons in the projectile frame. The horizontal bars show the angular spreads in the projectile frame. The uncertainty in the magnitude of the cross section is given by the scatter of the actual points.

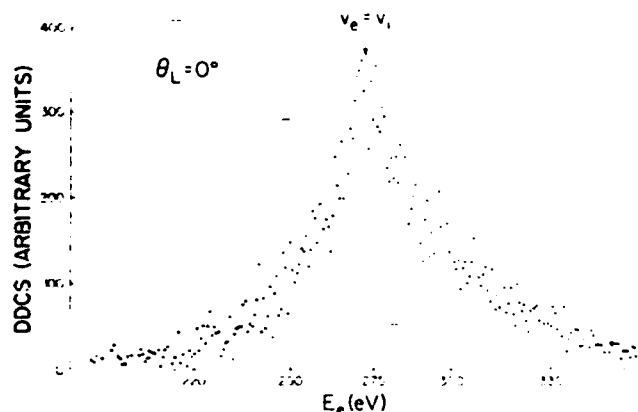Fig. 3 - From Ref. 3.

Fig. 4 - From Ref. 4.

FIG. 3. The electron energy spectrum which results when one subtracts the accidental spectrum from the correlated-plus-accidental spectrum as discussed in the text.
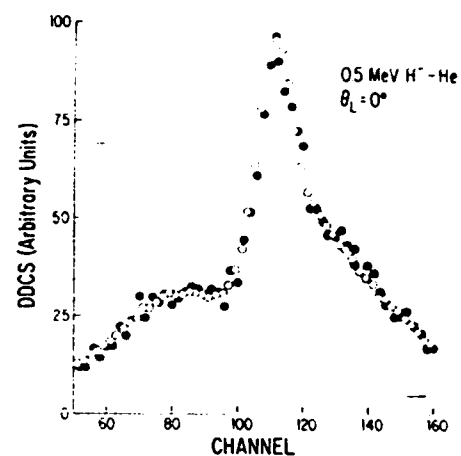
Fig. 5 - From Ref. 5.

FIG. 2. The total electron energy spectrum at $\theta_L - 0°$ is shown by the open circles (○). The e-H time-correlated electron-energy spectrum is shown by the solid dots (●). The two spectra have been normalized to the same number of counts in the peak at channel 111. (In the interest of clarity only one-half of the data points are plotted.)

Fig. 6 - From Ref. 4.

Table 1

E_i/amu	$\bar{E}$(eV)	$\frac{1}{2}M_e v^2$(eV)	$\delta\theta$ (deg)
0.7 MeV/amu	388.0	380.8	1-1.5
0.5 MeV/amu	277.5	272	3-4
0.25 MeV/amu	140.8	136	3-5
0.15 MeV/amu	84.9	81.6	4-6
0.1 MeV/amu	56.5	54.4	5-7

Table 1. - From Ref. 6.

COLLISIONAL SINGLE ELECTRON LOSS OF 0.5 MeV H⁻:
ENERGY SPECTRUM OF DETACHED ELECTRONS COINCIDENT WITH THE
FORMATION OF H(2p)

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Abstract

We have measured the energy spectrum of detached electrons at $\theta_L = 0°$ in coincidence with Lyman-α photons from the excitation and subsequent decay of H(2p) produced during the process, $H^- + He \rightarrow H(2p) + e^- + He^*$, at 0.5 MeV incident ion energy. We find that this electron energy distribution mimics the so-called very sharp peak feature of the doubly differential cross section previously measured under e^--H coincidence conditions. This result shows that excitation of H is responsible for the very sharp peak and that the detached electron energy distribution associated with H(2p) is significantly different from the distribution associated with the production of H(1s).

I. Introduction

In a recent paper[1] we summarized the features of the doubly differential cross section (DDCS) in the extreme forward direction in the laboratory frame, $0° \leq \theta_L \leq 3°$, of electrons ejected during single-electron-loss (SEL) processes of H^- incident on He at 0.5 MeV. In particular, it was shown that the very sharp peak at $v_e = v_i$, where v_e and v_i are the electron and ion laboratory speeds, respectively, is due to SEL processes and not to double-electron-loss processes.   Earlier work[2] had already established the fact that, in the H-frame, the shape of this very sharp peak is independent of whether the target is He or Ar, is independent of the incident ion energy in the range 100-700 KeV/u and that the angular distribution of these very low energy electrons is isotropic.   In light of these findings and on the basis of Born calculations[3,4] of the electron DDCS near $\theta_L = 0°$ for the specific SEL process

$$H^- + He \rightarrow H(1s) + e^- + He^* \tag{1}$$

and a preliminary Born calculation[6] that accounts for excitation of the H-atom to H(2s), it was conjectured in Ref. 1 that the most likely candidates responsible for this very sharp peak are SEL processes that produce excited H atoms.

Electron detachment collisions of H^- with H, H_2 and Ar are known to produce excited states of H. Excitation of H to highly

excited states has been measured in the incident energy range from 2.8-60KeV/u for the above systems.[6] The excitation yield was found to follow a $1/n^3$ scaling for highly excited states (n between 12 and 28) whereas the yield of n=2 and n=3 states was found to be higher than that estimated by $1/n^3$ scaling.[6,7] Since most of the excitation resides in the lower n states it is reasonable to address our conjecture regarding the energy distribution of detached electrons associated with excitation by selecting those electrons associated (coincident) with the production of H(2p).

In this paper we report on measurements of the detached electron energy spectrum at $\theta_L = 0°$ in coincidence with Lyman-α photons from the subsequent decay of H(2p) produced during the process.

$$H^- + He \rightarrow H(2p) + e^- + He^*. \qquad (2)$$

We note that the excitation of He was not specified in these measurements. The role of the mean excitation energy of the target has been theoretically established for process (1)[8] and, in principle, can be expected to play a role in process (2). Nevertheless, the role of target excitation appears to be relatively unimportant with regard to the energy distribution of detached electrons in process (2) since the shape of the very sharp peak is independent of the target[2] whereas the mean excitation energy depends on the target.[8]

The electron-Lyman-α photon coincidence DDCS was found to mimic the shape of the previously measured very sharp peak thus confirming our conjecture and the notion that excitation of H in the final state must be considered in order to fully account for the energy distribution of detached electrons.[4]

II.   Experimental Procedures

Detailed discussions of the apparatus and electronics used are given in Refs. 1 and 2. Additional details pertinent to this experiment are given below.

Small slots were cut in both the inner and outer cylinders of the cylindrical mirror electron energy analyzer in order to allow the photons to leave the analyzer. These slots were centered along the line traveled by the ion beam and positioned in such a manner that the photon detector could accept photons from the outer edge of the He cross beam to within 1 cm of the inner cylinder wall, a distance of approximately 1.5 cm. At 0.5 MeV incident energy the length of the viewed path approximately corresponds to the H(2p) decay time of 1.6 n sec. The Lyman-α photon detector consisted of a channeltron (Galileo #4039) preceded by a 1 mm thick LiF window. The overall acceptance solid angle of the photon detector was about 10^{-2} sr and had an estimated efficiency for Lyman-α photons between 0.1 and 1%. Since the photon detector was just able to view the outer edge of the He cross beam some of the detected photons may

have come from $He^+(n=4) \to He^+(n=2)$ transitions. Although photons from the He^+ transitions would be time-correlated to some electrons there is no reason to expect that the energy distribution of these electrons would be the same as the very sharp peak. Moreover, the shape of the very sharp peak is known to be the same for Ar as it is for He. Hence, all detected photons were attributed to the $H(2p) \to H(1s)$ transition.

The electrons were energy analyzed under the following analyzer conditions: $\Delta E/E = .014$, full width at half maximum; $\Delta\theta_L = 0.85°$. Under these analyzer conditions and the conditions noted above for the photon detector the maximum electron-Lyman-α photon coincidence count rate was about 0.01 sec^{-1} using a "clean" H^- beam (see Ref. 1) of about 4 namp with a diameter of 1.2 mm and He cross beam with a number density of about 10^{14} cm^{-3} and a 2-3 mm diameter. The electron-photon coincidence count rate was found to be negligible with the He cross beam off. The post-interaction beam was dumped into a Faraday cup and the collected charge was used to provide a normalization basis for the data.

The energy spectrum of electrons coincident with Lyman-α photons from the decay $H(2p) \to H(1s)$ was obtained as follows. The analyzer voltage was set to pass electrons of a given energy which were ultimately detected by a channeltron. Pulses from the electron channeltron were suitably amplified, delayed, and used as stop signals for a time-to-amplitude converter (TAC). The photon channeltron pulses were treated in a similar manner, except for a delay, and used to start the TAC. After the

accumulation of a TAC spectrum the process was repeated at another analyzer voltage. The standard coincidence circuitry was the same as that used in Ref. 1. The main difference between this coincidence experiment and our previous coincidence measurements is that the analyzer voltage was kept constant during a run instead of being swept. This procedure was dictated by the low coincidence rates which required 4-8 hour runs for just one electron energy. A typical TAC spectrum is shown in Fig. 1. The electron-photon coincidence counts were determined by subtracting the average accidental counts from the time correlated peak.

III. Results

The electron-Lyman-α photon coincidence DDCS at $\theta_L=0°$ is shown in Fig. 2. Also shown in Fig. 2 is the very sharp peak obtained previously by a subtraction process[2] but which has been averaged over the poorer energy resolution of the present work. Examples of the results of this subtraction process can be seen in Fig. 3 of Ref. 2. The very sharp peak was normalized at 272.8eV to the average electron-Lyman-α photon coincidence data from several runs at this energy.

One thing to note is that the electron-Lyman-α photon spectrum does not have the low energy peak seen in the high resolution uncorrelated spectra. (With the resolution of this experiment the peak appears as a prominent shoulder on the low energy side of the very sharp peak.) Inspection clearly shows

that there is no suggestion of a shoulder on the electron-photon coincidence spectrum but only a single peak. Thus, it is clear that the energy distribution of detached electrons associated with SEL processes producing H(2p) excitation is significantly different from SEL processes that produce H(1s).

With only a single peak in evidence in the coincidence spectrum it is clear that the interference between $l=0$ and $l=1$ electron partial waves is much less pronounced than it is for process (1) where a double-peaked structure is seen. This result is in qualitative agreement with the preliminary theoretical calculation that accounts for excitation to H(2s) where the effect of the interference between $l=0$ and $l=1$ was found to be greatly suppressed compared to the case where H is produced in the ground state.[6] Such a small interence effect would not be seen in our data.

We wish to point out that in other higher resolution data at 0.5 MeV, both with and without the e^{-}-H coincidence requirement (see Fig.2 of Ref. 1), there is no evidence of the excitation and subsequent decay of the $^1P^o$ shape resonance. Evidence of excitation of this resonance has been found using 100KeV H^{-}.[9] Although the resolution used in our work is not quite good enough to detect the resonance in competition with the direct excitation of H(2p) we note that the electron-Lyman-α photon coincidence measurement ought to be especially sensitive to the $^1P^o$ shape resonance. For example, if H(2p) excitations were fed

exclusively via the $^1P^o$ shape resonance, the electron energy distribution would be expected to show a pronounced dip[3] at $v_e = v_i$ which would be discernible at this resolution. Therefore, it seems that the excitation of the $^1P^o$ resonance channel must be quite small relative to direct H(2p) excitation above about 100 KeV.
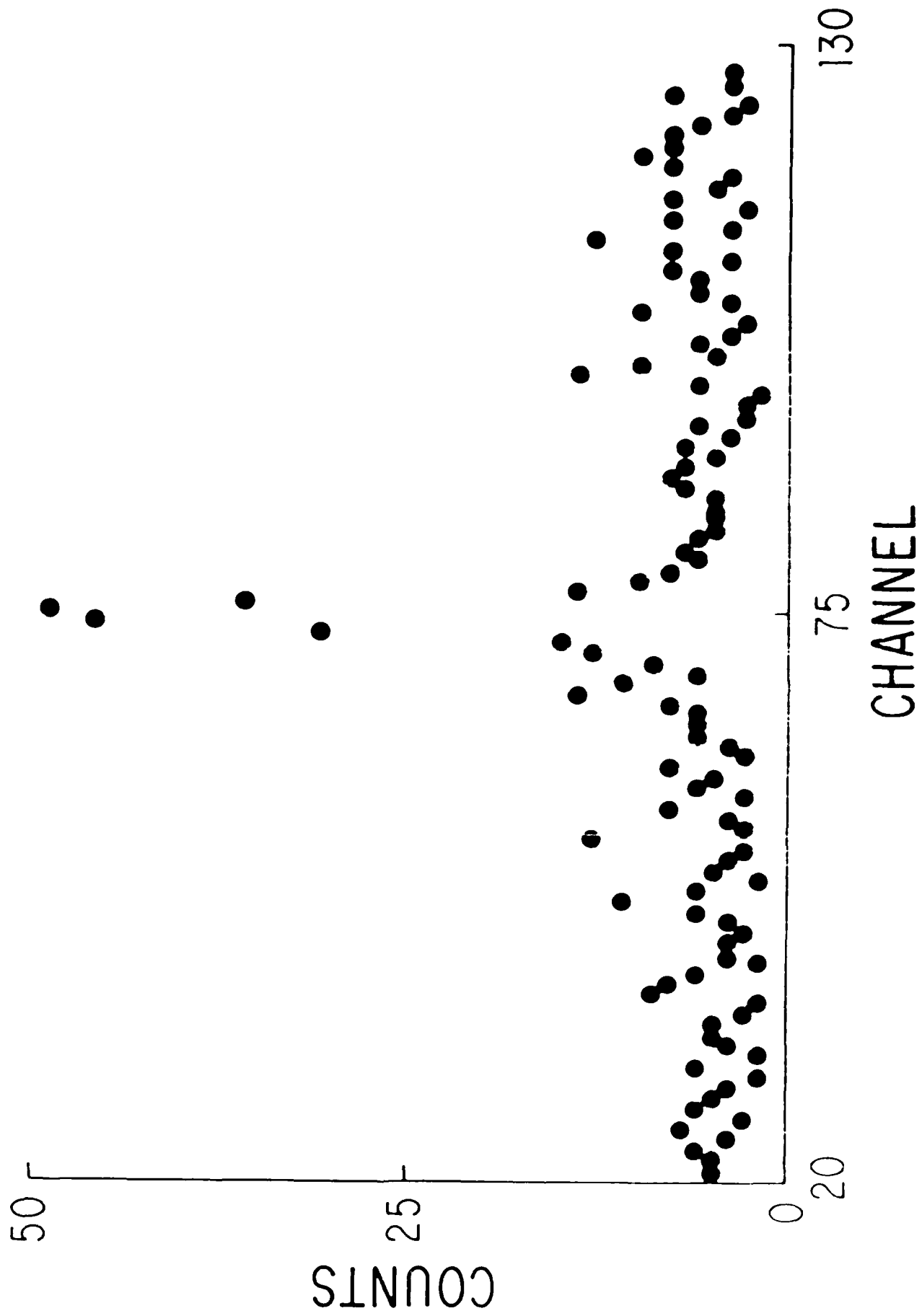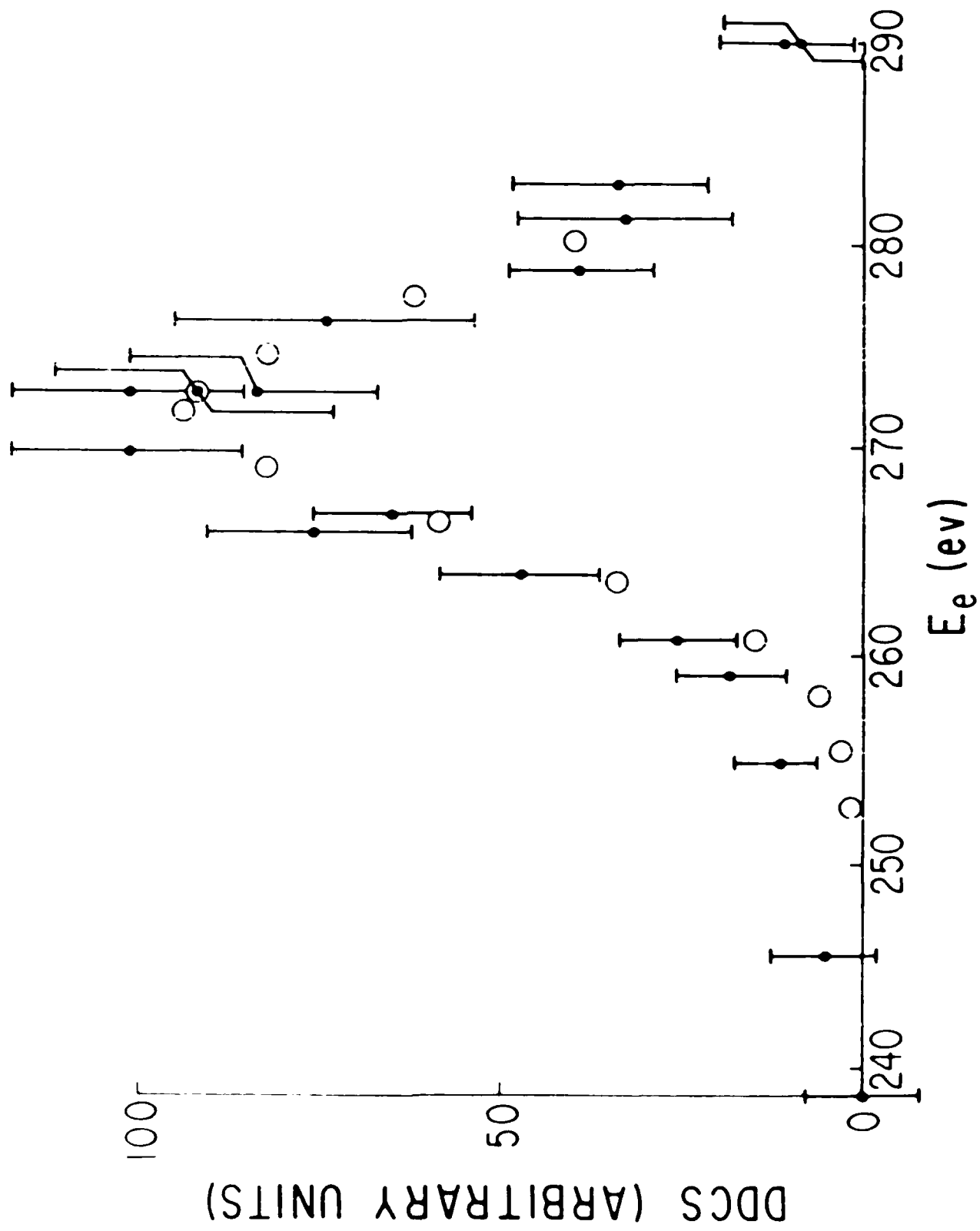
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FIGURE CAPTIONS

Figure 1. A typical output spectrum of the TAC set on the 200-nsec range with the analyzer voltage set to detect electrons near the peak of the DDCS. The stop leg of the TAC had a 100-nsec delay inserted.

Figure 2. Shown are the results of the electron-Lyman-α photon coincidences as a function of electron energy measured at $\theta_L = 0^\circ$ The open circles are the energy averaged DDCS of the very sharp peak as discussed in the text.

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